BNL-NCS--35513

DE85 005130

BNL-NCS-35513-R

A Reevaluation of the Average Prompt Neutron Emission Multiplicity (Nubar) Values from Fission of Uranium and Transuranium Nuclides

Norman E. Holden and Martin S. Zucker

Abstract

In response to a need of the safeguards community, we have begun an evaluation effort to upgrade the recommended values of the prompt neutron emission multiplicity distribution, P_ν and its average value, nubar. This paper will report on progress achieved thus far. The evaluation of the uranium, plutonium, americium and curium nuclide's nubar values will be presented. The recommended values will be given and discussed.

I. Introduction

The neutron emission multiplicity distribution, P_ν is the probability that a given fission will result in the emission of ν neutrons. The basic method used by all experimenters to generate P_ν data involves a way of detecting each fission as it occurs in a sample of the nuclide under study and correlates this fission with the detection of the emitted neutrons. Since the efficiency, ε, of the neutron detector for the detection of a single neutron is less than unity, allowance for those neutrons emitted but not detected must be made, with the resulting probability Q_n of actually observing n neutrons even if ν were emitted ($n < \nu$) being just:

$$Q_n = \Sigma P_\nu [\nu!/n!(\nu-n)!] \varepsilon^n (1-\varepsilon)^{\nu-n} \quad (1)$$

The P_ν are constants of nature, whereas the Q_n depend on the efficiency of the particular detector used. From the above expression it follows directly that P_ν is given in terms of the observed relative frequencies of observation Q_n by the expression:

$$P_\nu = \Sigma Q_n [n!/\nu!(n-\nu)!] \varepsilon^{-n} (\varepsilon-1)^{n-\nu} \quad (2)$$

Knowledge of the detector efficiency which is essential to relate the observed frequencies Q_n, to the multiplicities, P_ν, is usually determined from the count rate with a calibrating nuclide, whose nubar value is well known.

$$g = \varepsilon \langle\nu\rangle q \quad (3)$$

where q is the fission rate of the sample of the calibrating nuclide and g is the gross count rate for the calibrating nuclide. (The efficiency is thus inversely related to the assumed value of $\langle\nu\rangle$.) This is possible because $\langle\nu\rangle$ can be determined independently of the determination of P_ν and with greater accuracy than if it were calculated from the P_ν distribution using

$$\langle\nu\rangle = \Sigma \nu P_\nu. \quad (4)$$

In deriving the $\langle\nu\rangle$ values for the various nuclides, one standard value is assumed, for ^{252}Cf. From an earlier evaluation[1], a value of $\langle\nu\rangle = 3.757 \pm 0.010$ neut/fiss is derived.

In the following sections, we will review the direct determination of $\langle\nu\rangle$ values and then describe the method of comparing different sets of P_ν values.

II. The Fissile Nuclides, ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu.

Of the various nubar values that have been determined, those for the fission via thermal neutrons of the four fissile elements have a special importance because of the thermal reactor program. They are important parameters in the least squares fit that determines the various neutron cross sections of these nuclides needed for reactor operation.

DISCLAIMER

The most careful experiments on nubar have been those which compared the thermal neutron fission value for the fissile nuclide with the nubar value for spontaneous fission of ^{252}Cf. Table I lists the various experimental results for prompt nubar of ^{233}U to that of ^{252}Cf, while Tables II, III, and IV list similar results for ^{235}U, ^{239}Pu and ^{241}Pu, respectively. The reported values are listed along with the revised values based on an evaluation of each experiment.

Some general comments can be made about these Tables. Corrections were made for the effect of delayed gamma-rays, the effect of the different mean energies for the various fission neutron spectra involved, and for the loss of those events corresponding to fission fragments of low energy because of the thickness of the fission foil. Low kinetic energy fission fragments correspond to the release of higher numbers of neutrons and therefore thick foils depress the nubar value as a result.

The delayed gamma-ray effect was taken from Boldeman's 1977 review[2] without change. The mean energies of the fission spectrum were also taken from the same review except for ^{252}Cf, which came from the 1979 measurement of Boldeman[3]. However, the uncertainty included 50% for the shape of the efficiency curve and an additional uncertainty corresponding to the spread between the energy differences used in this calculation and the energy differences measured by Smith[4].

For some of the measurements, the ratios were determined for a neutron in the kev energy range and extrapolated back to a thermal value using a curve with a constant slope, which had been fit between the value at thermal energies and the value at 2 Mev. However, it is not clear that application of this constant slope is appropriate at 30-60 kev energy range. In fact, data from Gwin[5] and Prokhorova[6] would imply that the ratio ($\langle\nu\rangle$-^{235}U/$\langle\nu\rangle$-^{252}Cf) is slightly smaller in the 50-100 kev energy region than at thermal neutron energies. It is clear that in the region 0.5 - 1.0 Mev, the ratio is definitely larger. Until we can better evaluate this effect, we felt that our choice was either to discard these measurements or to assume that the 30 - 60 kev ratio was equivalent to the thermal value. We have chosen the latter assumption in this paper but have added the effect of the constant slope assumption as an uncertainty rather than as a correction.

For the foil thickness correction, we used three estimates; Gwin[7] - for Gwin's measurement, Malinovskii[8] - for the Obninsk measurements and Boldeman[9] - for all other measurements. Although we would agree with Gwin that the foil thickness corrections should preferably be determined for the exact geometrical arrangements of each experiment, when this is not yet available, we prefer to apply some correction rather than no correction at all for this effect. We have assumed a 50% uncertainty on this correction.

III Method of Comparing Different P_ν Sets.

The Q_n and P_ν can be considered vectors, whose components are probabilities, related by an operation and its inverse which converts one set of probabilities into the other, i.e. equation (1) and (2). Certain ratios composed of specific functions of the various moments of the distributions are independent of the efficiency, e.g. $\langle\nu(\nu-1)....(\nu-k)\rangle / \langle\nu\rangle^{k+1} = \langle n(n-1)...(n-k)\rangle / \langle n\rangle^{k+1}$. A particular case is Diven's parameter, for k = 1, $\langle\nu(\nu-1)\rangle / \langle\nu\rangle^2$, which can be considered as a measure of the shape of the P_ν distribution. However, another indicator of the distribution's shape, which is not conserved, (independent of ε) is the ratio of the mean square deviation to the square of the mean : $\langle(\nu-\langle\nu\rangle)^2\rangle / \langle\nu\rangle^2 = (\langle\nu^2\rangle - \langle\nu\rangle^2) / \langle\nu\rangle^2$.

For each given experiment, the equations (1) and (2) were used with the quoted distribution P_ν and the reported efficiency ε to derive the original Q_n set. The efficiency was then varied until the calculated $\langle\nu\rangle$ ($\Sigma\ \nu\ P_\nu$) value was obtained corresponding to the recommended value. In those few cases where the experimentalist did not report the efficiency, a reasonable value was assumed appropriate to the experimental conditions and then the above procedure was also followed.

After various sets of P_ν for the same nuclide are transformed so that each set yields the same $\langle\nu\rangle$, any remaining differences between the corresponding P_ν can be ascribed to systematic errors other than those in ε or $\langle\nu\rangle$, or to random errors (e.g. counting statistics) in the respective experiments. Evaluation of the standard deviation of corresponding values of P_ν gives a realistic estimate of the uncertainty involved in determining the P_ν. Our earlier work[10] contains more details on the method.

IV Recommendations and Discussion

The recommended values for <ν> and P_ν for the various nuclides of uranium, plutonium, americium and curium are given in the Tables in section VII. The special importance of the <ν> values for the fissile nuclides was mentioned earlier in this paper. Additional work is planned to investigate the dν/dE variation and the mean energy difference between the various fission neutron spectra and their effects on the reported results. In this first study, it is not clear whether the recommended uncertainties in the <ν> ratios, 0.16%–0.18%, are underestimated because of correlations. This possibility will also be investigated later.

V Acknowledgements

The authors acknowledge helpful discussions with Mulki Bhat (BNL), Reg Gwin (ORNL), Joe Halperin (ORNL), Bob Howe (LRL) and Alan Smith (ANL). In addition, John Boldeman's release of a recent revision of his data prior to publication for our use is greatly appreciated.

VI References

1. N.E.Holden and M.S.Zucker, Proc. ANS/INMM Topical Meeting on Safeguards and Technology. Hilton Head, S.C., Nov.28–Dec.2,1983. Trans. Amer. Nucl. Soc. 45, suppl.1, 23 (1983).
2. J.W.Boldeman, Proc. Int. Specialist's Symp. on Neut. Standards and Appl. Gaithersberg, Md., Mar. 28–31,1977. NBS Spec. Pub. 493, 182 (1977).
3. J.W.Boldeman, D.Culley and R.J.Crawley, Trans. Amer. Nucl. Soc. 32, 735 (1979).
4. A.B.Smith, P.Guenther, G.Winkler and R.McKnight, Nucl. Sci. Eng. 76, 357 (1980).
5. R.Gwin et al., ORNL–TM–7148 (1980).
6. L.I.Prokhorova et al., Sov. Atom. Energy 30, 307 (1971).
7. R.Gwin, R.R.Spencer and R.W.Ingle, Nucl. Sci. Eng. 87, 381 (1984).
8. V.V.Malinovskii et al., Sov. Atom. Energy 55, 501 (1984).
9. J.W.Boldeman and J.Frehaut, Nucl. Sci. Eng. 76, 49 (1980).
10. M.S.Zucker and N.E.Holden, Proc. 6th ESARDA Symp. on Safeguards and Nucl. Material Management. Venice, Italy, May 14–18,1984. p.341.
11. B.Nurpeisov et al., Sov. Atom. Energy 34, 603 (1973).
12. J.W.Boldeman and A.W.Dalton, AAEC/E–172 (1967).
13. S.C.Fultz et al., Phys. Rev. 152, 1046 (1966).
14. D.W.Colvin and M.G.Sowerby, Proc. Symp. on Phys. Chem of Fission. Salzburg, Austria,Mar.22–26,1965 Vol.2, 25 (1965).
15. D.S.Mather, P.Fieldhouse and A.Moat, Nucl. Phys. 66, 149 (1965).
16. J.C.Hopkins and B.C.Diven, Nucl. Phys. 48, 433 (1963).
17. A.DeVolpi and K.G.Porges, Proc. Int. Conf. on Nucl. Data for Reactors. Paris, France,Oct. 17–21,1966. Vol.2, 297 (1967).
18. H.Conde, Ark. Fys. 29, 293 (1965).
19. D.S.Mather, P.Fieldhouse and A.Moat, Phys. Rev. 133, 1403 (1964).
20. J.W.Meadows and J.F.Whalen, Phys. Rev. 162, 197 (1962).
21. K.E.Bolodin et al., Sov. Atom. Energy 33, 1045 (1973).
22. M.Divadeenam and J.R.Stehn, Ann. Nucl. Energy 11, 375 (1984).
23. E.J.Axton, Eur. Appl. Res. Rep. – Nucl. Sci. Technol. Sect. 5, 609 (1984).
24. J.R.Stehn, M.Divadeenam and N.E.Holden, Int. Conf. on Nucl. Data for Sci. Technol.Antwerp, Belgium, Sept. 6–10,1982.
25. A.H.Jaffey and J.L.Lerner, Nucl. Phys. A145, 1 (1970).
26. S.N.Belenky, M.D.Skorokhvatov and A.V.Etenko, Sov. Atom. Energy 55, 528 (1983).
27. H.Conde and M.Holmberg, J. Nucl. Energy 25, 331 (1971).
28. A.G.Popeko et al., Sov. J.Nucl. Phys. 24, 245 (1976).
29. S.N.Hwang et al., Acta Phys. Sinica 23, 46 (1974).
30. I.Asplund–Nilsson et al., Nucl. Sci. Eng. 15, 213 (1963).
31. R.Sher and J.Leroy, J. Nucl. Energy 12, 101 (1960).
32. B.D.Kuz'minov et al., Sov. Phys. JETP 37, 290 (1960)
33. K.W.Geiger and D.C.Rose, Can. J. Phys. 32, 498 (1954).
34. D.A.Hicks, J.Ise,Jr. and R.V.Pyle, Phys. Rev. 101, 1016 (1956).
35. C.J.Orth, Nucl. Sci. Eng. 43, 54 (1971).
36. J.W.Boldeman, priv. comm. Oct. 1984.

37. H.Zhang, Z.Liu, S.Ding and S.Liu, Nucl. Sci. Eng. 86, 315 (1984).
38. J.Frehaut, G.Mosinski, R.Bois and M.Soleilhac, CEA-R-4626 (1974).
39. H.Zhang and Z.H.Liu, Chin. J. Nucl. Phys. 1, 9 (1972).
40. E.Baron, J.Frehaut, F.Ouvry and M.Soleilhac, Proc. Int. Conf. Nucl. Data for Reactors.Paris, France, Oct. 17-21,1966 Vol.2, 57 (1967).
41. B.C.Diven and J.C.Hopkins, Proc. Sem. Phys. of Fast and Intermediate Reactors. Vienna,Austria, Aug. 3-11,1961 Vol 1, 111 (1962).
42. A.Moat, D.S.Mather and M.H.McTaggert, J. Nucl. Energy 15, 102 (1961).
43. B.C.Diven, H.C.Martin, R.F.Taschek and J.Terrell, Phys. Rev. 101, 1012 (1956).
44. G.Edwards, D.J.S.Findlay and E.W.Lees, Ann. Nucl. Energy 9, 127 (1982).
45. L.Prokhorova, G.N.Smirenkin and Yu.M.Turchin, Sov. Atom. Energy 25, 1369 (1969).
46. V.I.Lebedev and V.I.Kalashnikova, Sov. Atom. Energy 5, 90 (1958).
47. J.G.Cuninghame, J. Inorg. Nucl. Chem. 4, 1 (1957).
48. R.E.Howe et al., Nucl. Sci. Eng. 77, 454 (1981).
49. N.I.Kroshkin and Yu.S.Zamyatnin, Sov. Atom. Energy 29, 790 (1970).
50. J.Halperin et al., Nucl. Sci. Eng. 75, 56 (1980).
51. W.W.T.Crane, G.H.Higgins and H.R.Bowman, Phys. Rev. 101, 1804 (1956).
52. K.D.Zhuraviev, Yu.S.Zamyatnin and N.I.Kroshkin, Nat. Sov. Conf. on Neut. Phys. Kiev, USSR May 28-Jun.1,1973 Vol.4, 57 (1974).
53. R.Schmidt and H.Henschel, Nucl. Phys. A395, 29 (1983).
54. V.V.Golushko et al., Sov. Atom. Energy 34, 178 (1973).
55. L.I.Prokhorova et al., Sov. Atom. Energy 33, 875 (1973).
56. V.I.Bol'shov, L.I.Prokhorova, V.N.Okolovich and G.N.Smirenkin, Sov. Atom. Energy 17, 715 (1964).
57. R.E.Howe et al., Nucl. Phys. A407, 193 (1983).
58. R.W.Stoughton, J.Halperin, C.E.Bemis and H.W.Schmitt, Nucl. Sci. Eng. 50, 169 (1973).
59. D.M.Dakovskii, Yu.A.Lazarev and Yu.Ts.Oganesyan, Sov. J. Nucl. Phys. 18, 371 (1974).
60. M.C.Thompson, Phys. Rev. C2, 763 (1970).
61. J.W.Boldeman, Nat. Sov. Conf. on Neut. Phys. Kiev, USSR May 28-Jun.1,1973 Vol.4, 114 (1974).

VII Tabulated Results

Table I Measured Nubar ratios for $^{233}U/^{252}Cf$

Author (Year)	Ref. No.	Reported Ratio	Revised Ratio	Comment
Gwin(84)	7	0.6597 (0.0018)	0.6581 (0.0023)	
Nurpeisov(72)	11	0.6615 (0.0027)	0.6592 (0.0039)	
Boldeman(67)	12	0.6586 (0.0021)	0.6604 (0.0017)	
Fultz(66)	13	0.6720 (0.011)	0.6747 (0.0111)	Discarded-test value
Colvin(65)	14	0.6551 (0.0049)	0.6565 (0.0050)	
Mather(64)	15	0.6698 (0.0082)	0.6713 (0.0083)	
Hopkins(63)	16	0.6558 (0.0069)	0.6548 (0.0069)	

Table II Measured Nubar ratios for $^{235}U/^{252}Cf$

Author (Year)	Ref. No.	Reported Ratio	Revised Ratio	Comment
Gwin(84)	7	0.6443 (0.0014)	0.6438 (0.0015)	
Prokhorova(70)	6	0.6379 (0.0037)	0.6417 (0.0045)	
Boldeman(67)	12	0.6385 (0.0021)	0.6406 (0.0017)	
DeVolpi(66)	17	0.640 (0.011)	0.633 (0.027)	Discarded-discrepant data
Fultz(66)	13	0.6429 (0.0212)	0.6451 (0.0213)	Discarded-test value
Conde(65)	18	0.6400 (0.0053)	0.6433 (0.0055)	
Colvin(65)	14	0.6423 (0.0029)	0.6437 (0.0030)	
Mather(64)	19	0.6378 (0.0032)	0.6398 (0.0037)	
Hopkins(63)	16	0.6431 (0.0058)	0.6438 (0.0059)	
Meadows(61)	20	0.6449 (0.0104)	0.6412 (0.0092)	

Table III Measured Nubar ratios for $^{239}Pu/^{252}Cf$

Author (Year)	Ref. No.	Reported Ratio	Revised Ratio
Gwin(84)	7	0.7655 (0.0014)	0.7652 (0.0015)
Bolodin(73)	21	0.7679 (0.0040)	0.7666 (0.0076)
Boldeman(67)	12	0.7674 (0.0021)	0.7670 (0.0021)
Colvin(65)	14	0.7592 (0.0062)	0.7616 (0.0062)
Mather(64)	15	0.7750 (0.0090)	0.7735 (0.0091)
Hopkins(63)	16	0.7507 (0.0074)	0.7499 (0.0074)

Table IV Measured Nubar ratios for $^{241}Pu/^{252}Cf$

Author (Year)	Ref. No.	Reported Ratio	Revised Ratio
Gwin(84)	7	0.7820 (0.0018)	0.7820 (0.0018)
Boldeman(67)	12	0.7788 (0.0018)	0.7784 (0.0019)
Colvin(65)	14	0.7771 (0.0079)	0.7788 (0.0079)

Table V Comparison of Recent Recommended Nubar Ratios for the Fissile Nuclides

Author(Year)	Ref.	$^{233}U/^{252}Cf$	$^{235}U/^{252}Cf$	$^{239}Pu/^{252}Cf$	$^{241}Pu/^{252}Cf$
This paper	-	0.6595 (0.0012)	0.6424 (0.0010)	0.7654 (0.0012)	0.7803 (0.0013)
Divadeenam(84)	22	0.6615 (0.0010)	0.6407 (0.0008)	0.7636 (0.0014)	0.7771 (0.0018)
Axton(84)	23	0.6603 (0.0015)	0.6416 (0.0012)	0.7638 (0.0016)	0.7800 (0.0017)
Stehn(82)	24	0.6610 (0.0015)	0.6421 (0.0011)	0.7648 (0.0015)	0.7784 (0.0018)
Boldeman(80)	9	0.6597 (0.0014)	0.6403 (0.0011)	0.7651 (0.0018)	0.7781 (0.0018)

Table VI Measured Nubar values for ^{232}U and ^{236}U

Nuclide	Author(Year)	Ref.	Measured Value	Revised Value
232U	Jaffey(70)	25	3.13 (0.06)	3.14 (0.06)
236U	Belenky(83)	26	1.79 (0.18)	
236U	Conde(71)	27	1.90 (0.05)	

Table VII Measured Nubar values for ^{238}U

Author(Year)	Ref.	Measured Value	Revised Value
Belenky(83)	26	1.97 (0.10)	
Popeko(76)	28	1.99 (0.03)	2.03 (0.03)
Hwang(74)	29	1.96 (0.05)	
Conde(71)	27	2.00 (0.05)	
Asplund-Nilsson(63)	30	1.97 (0.07)	1.95 (0.07)
Sher(60)	31	2.10 (0.08)	2.05 (0.08)
Kuz'minov(59)	32	2.08 (0.08)	1.98 (0.08)
Geiger(54)	33	2.26 (0.16)	

Table VIII Measured Nubar values for ^{236}Pu, ^{238}Pu and ^{244}Pu

Nuclide	Author(Year)	Ref.	Measured Value	Revised Value	Comment
236Pu	Hicks(56)	34	2.305 (0.19)	2.17 (0.19)	Spont.Fiss.
238Pu	Hicks(56)	34	2.33 (0.08)	2.21 (0.08)	Spont.Fiss.
238Pu	Jaffey(70)	25	2.90 (0.03)	2.89 (0.03)	Neut. Fiss.
238Pu	Kroshkin(70)	49	2.92 (0.12)	2.90 (0.12)	Neut. Fiss.
244Pu	Orth(71)	35	2.30 (0.19)	2.29 (0.19)	Spont.Fiss.

Table IX Measured Nubar values for ^{240}Pu

Author (Year)	Ref.	Measured Value	Revised Value
Boldeman(84)	36	2.156 (0.010)	
Zhang(84)	37	2.141 (0.016)	2.149 (0.016)
Frehaut(74)	38	2.148 (0.015)	2.162 (0.015)
Prokhorova(71)	6	2.161 (0.016)	
Zhang(71)	39	2.138 (0.031)	
Baron(67)	40	2.153 (0.020)	2.139 (0.020)
Colvin(65)	14	2.118 (0.018)	2.144 (0.014)
Asplund-Nilsson(63)	29	2.154 (0.028)	2.130 (0.028)
Hopkins(63)	16	2.19 (0.03)	2.18 (0.03)
Diven(62)	41	2.167 (0.036)	
Moat(61)	42	2.13 (0.05)	2.169 (0.05)
Diven(56)	43	2.257 (0.045)	2.215 (0.045)

Table X Measured Nubar values for ^{242}Pu

Author (Year)	Ref.	Measured Value	Revised Value
Edwards(82)	44	2.153 (0.014)	2.156 (0.014)
Boldeman(84)	36	2.145 no uncert.	
Prokhorova(69)	45	2.13 (0.05)	2.14 (0.05)
Hicks(56)	34	2.18 (0.09)	2.07 (0.09)

Table XI Measured Nubar values for ^{241}Am

Author (Year)	Ref.	Measured Value	Revised Value	Comment
Jaffey(70)	25	3.219 (0.021)		
Lebedev(58)	46	3.14 (0.05)	3.07 (0.05)	No efficiency correction
Cuninghame(57)	47	3. (0.5)		Calc. from Fission Yields

Table XII Measured Nubar values for ^{242m}Am

Author (Year)	Ref.	Measured Value	Revised Value
Howe(81)	48	3.269 (0.145)	
Jaffey(70)	25	3.264 (0.024)	3.265 (0.024)
Fultz(66)	13	3.24 (0.12)	3.22 (0.12)
Kroshkin(70)	49	3.28 (0.10)	3.26 (0.10)

Table XIII Measured Nubar Values for ^{242}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Zhang(84)	37	2.562 (0.020)	2.572 (0.020)
Halperin(80)	50	2.532 (0.013)	2.530 (0.013)
Hicks(56)	34	2.65 (0.09)	2.53 (0.09)
Crane(55)	51	2.33 (0.11)	2.48 (0.11)

Table XIV Measured nubar Values for ^{243}Cm, ^{247}Cm and ^{250}Cm

Nuclide	Author (Year)	Ref.	Measured Value	Revised Value	Comment
243Cm	Zhuraviev(73)	52	3.39 (0.14)	3.40 (0.04)	Neut. Fiss.
243Cm	Jaffey(70)	25	3.430 (0.047)	3.432 (0.047)	Neut. Fiss.
247Cm	Zhuraviev(73)	52	3.79 (0.15)	3.80 (0.15)	Neut. Fiss.
250Cm	Orth(71)	35	3.31 (0.08)	3.30 (0.08)	Spont.Fiss.

Table XV Measured Nubar Values for ^{244}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Zhang(84)	37	2.72 (0.02)	2.74 (0.02)
Schmidt(83)	53	2.73 (0.16)	2.74 (0.16)
Golushko(73)	54	2.68 (0.03)	
Prokhorova(73)	55	2.70 (0.014)	
Jaffey(70)	25	2.692 (0.024)	2.700 (0.024)
Kroshkin(70)	49	2.77 (0.08)	2.76 (0.08)
Bol'shov(64)	56	2.71 (0.04)	2.69 (0.04)
Diven(56)	43	2.81 (0.06)	2.68 (0.06)
Hicks(56)	34	2.84 (0.09)	2.71 (0.09)

Table XVI Measured Nubar Values for ^{245}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Howe(83)	57	3.60 (0.06)	3.64 (0.06)
Kroshkin(70)	49	3.83 (0.16)	3.81 (0.16)
Jaffey(70)	25	3.832 (0.034)	3.84 (0.03)

Table XVII Measured Nubar Values for ^{246}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Stoughton(73)	58	2.86 (0.06)	2.88 (0.06)
Dakovskii(73)	59	2.98 (0.03)	3.01 (0.03)
Golushko(73)	54	2.927 (0.027)	2.93 (0.03)
Prokhorova(72)	55	2.950 (0.015)	2.95 (0.015)
Thompson(70)	60	3.20 (0.22)	3.17 (0.22)

Table XVIII Measured Nubar Values for ^{248}Cm

Author (Year)	Ref.	Measured Value	Revised Value
Boldeman(73)	61	3.092 (0.007)	3.12 (0.007)
Stoughton(73)	58	3.14 (0.06)	3.16 (0.06)
Golushko(73)	54	3.173 (0.022)	3.17 (0.02)
Prokhorova(72)	55	3.157 (0.015)	3.16 (0.015)
Orth(71)	35	3.11 (0.09)	3.10 (0.09)

Table XIX Recommended Nubar Values for U, Pu, Am and Cm Nuclides

Nuclide	Value (Uncert.)	Nuclide	Value (Uncert.)
^{232}U	3.14 (0.06)	^{241}Am	3.22 (0.04)
^{233}U	2.485 (0.008)	^{242m}Am	3.26 (0.03)
^{235}U	2.414 (0.007)	^{242}Cm	2.54 (0.02)
^{236}U	1.89 (0.05)	^{243}Cm	3.43 (0.14)
^{238}U	1.98 (0.03)	^{244}Cm	2.72 (0.02)
^{236}Pu	2.17 (0.19)	^{245}Cm	3.75 (0.10)
^{238}Pu	2.21 (0.08)	^{246}Cm	2.93 (0.03)
^{239}Pu	2.876 (0.009)	^{247}Cm	3.80 (0.15)
^{240}Pu	2.154 (0.005)	^{248}Cm	3.13 (0.03)
^{241}Pu	2.932 (0.009)	^{250}Cm	3.30 (0.08)
^{242}Pu	2.149 (0.008)		
^{244}Pu	2.29 (0.19)		

Table XX

P_ν for (^{233}U+n)

	Gwin 84	Boldeman 84	Consensus	Std. Dev.
P_0	.0249152	.0266448	.0257800	.0012
P_1	.1517652	.1548291	.15329715	.0022
P_2	.3344314	.3289952	.3317133	.0038
P_3	.3225796	.3254248	.3240022	.0020
P_4	.1377542	.1296900	.13372210	.0057
P_5	.0259051	.0293501	.0276276	.0024
P_6	.0024540	.0050659	.00375995	.0018
P_7	.00019543	.0	.0000977	.0001
$\langle\nu\rangle$	2.48500000*	2.48500000*	2.48500000*	.008
$\langle\nu(\nu-1)\rangle$	4.8573	4.9058	4.8816	.0343
$\langle\nu(\nu-1)(\nu-2)\rangle$	7.1314	7.4340	7.2827	.2140
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.78658	.79443	.79051	.00555
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.1671	1.2156	1.1913	.0343
$\langle\nu^2\rangle$	7.3423	7.3908	7.3666	.0343

* data sets made to conform to this value

Table XXI

P_ν for (^{235}U+n)

	Gwinn 84	Boldeman 84	Consensus	Std. Dev.
P_0	.0306776	.0327670	.0317223	.0015
P_1	.1707282	.1726860	.1717071	.0014
P_2	.3384084	.3339897	.3361991	.0031
P_3	.3036614	.3042775	.3039695	.0004
P_4	.1295224	.1243698	.1269459	.0036
P_5	.0248181	.0285404	.0266793	.0026
P_6	.0019968	.0032675	.0026322	.0009
P_7	.0001872	.0001026	.0001449	.00006
$\langle\nu\rangle$	2.4140000*	2.4140000*	2.4140000*	.007
$\langle\nu(\nu-1)\rangle$	4.6172	4.6592	4.6382	.0297
$\langle\nu(\nu-1)(\nu-2)\rangle$	6.6985	6.9366	6.8176	.1683
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.79232	.79954	.79593	.00510
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.2038	1.2458	1.2248	.0297
$\langle\nu^2\rangle$	7.0312	7.0732	7.0522	.0297

• data sets made to conform to this value

Table XXII

P_ν for ^{238}U

	Hwang 74	Popeko 76	Consensus	Std. Dev.
P_0	.0443354	.0520000	.0481677	.0054
P_1	.2200429	.2770000	.2485215	.0403
P_2	.4846087	.3660000	.4253044	.0839
P_3	.2098187	.2470000	.2284094	.0263
P_4	.0346876	.0500000	.0423438	.0108
P_5	.0065066	.0080000	.0072533	.0011
$\langle\nu\rangle$	1.99000000*	1.9900000*	1.9900000*	.03
$\langle\nu(\nu-1)\rangle$	2.7745	2.9740	2.8743	.1411
$\langle\nu(\nu-1)(\nu-2)\rangle$	2.4818	3.1620	2.8219	.4810
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.70062	.75099	.72553	.03601
$\langle\nu^2\rangle-\langle\nu\rangle^2$	.8044	1.0039	.9022	.1411
$\langle\nu^2\rangle$	4.7645	4.9640	4.8643	.1411

* data sets made to conform to this value

	P_ν for ^{236}Pu		P_ν for ^{238}Pu	
	Hicks 56	** Std.Dev.	Hicks 56	** Std.Dev.
P_0	.0706805	.035	.0540647	.009
P_1	.1862416	.090	.2053880	.026
P_2	.3795474	.13	.3802279	.026
P_3	.2545524	.12	.2248483	.027
P_4	.0838837	.086	.1078646	.021
P_5	.0250943	.036	.0276366	.009
$\langle\nu\rangle$	2.17000000*	±.19	2.21000000*	±.08
$\langle\nu(\nu-1)\rangle$	3.7949		3.9567	
$\langle\nu(\nu-1)(\nu-2)\rangle$	5.0462		5.5960	
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.80590		.81011	
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.2560		1.2826	
$\langle\nu^2\rangle$	5.9649		6.1667	

* data sets made to conform to this values

** as assigned by author

Table XXIV

P_ν for (^{239}Pu+n)

	Diven** 56	Gwin 84	Boldeman 84	Consensus	Std. Dev.
P_0	.0059460-	.0108072	.0109130	.0108601	.00003
P_1	.1186641	.0973017	.1013071	.0993044	.0028
P_2	.1914874-	.2746513	.2750961	.2748737	.0003
P_3	.4899114+	.3299645	.3241354	.3270500	.0041
P_4	.1012346-	.2110361	.1984958	.2047660	.0087
P_5	.0568506	.0633398	.0822041	.0727720	.0133
P_6	.0359059+	.0116376	.0078484	.0097430	.0027
P_7	.0000000	.0012619	.0000000	.0006310	.0009
$\langle\nu\rangle$	2.8760000*	2.8760000*	2.8760000*	2.8760000*	.009*
$\langle\nu(\nu-1)\rangle$	6.7514	6.7304	6.7565	6.7435	.0184
$\langle\nu(\nu-1)(\nu-2)\rangle$	13.00888	12.5066	12.5828	12.5447	.0539
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.81624	.81370	.81685	.81528	.00223
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.3561	1.3351	1.3611	1.3481	.0184
$\langle\nu^2\rangle$	9.6274	9.6064	9.6325	9.6195	.0184

• data sets made to conform to this value

** set not used to arrive at consensus because of large divergences from more recent data

P_ν for ^{240}Pu

	Hammel** 55	Hicks** 56	Diven 56	Baron 66	Wang 74	Zhang 84	Boldeman 84	Consensus	Std. Dev.
P_0	.0674770	.0518555-	.0598767	.0672230	.0602461	.0628325	.0657477	.0631852	.0033
P_1	.2123022-	.2412679+	.2346677	.2296671	.2323636	.2307696	.2323544	.2319644	.0019
P_2	.3709042+	.3512038	.3290595	.3287954	.3417481	.3380100	.3290022	.3333230	.0061
P_3	.2208222-	.2298913-	.2625685+	.2535573	.2502577	.2466918	.2510283	.2528207	.0060
P_4	.1050492	.1090102	.0963776	.0996201	.0945106	.1015568	.1011654	.0986461	.0031
P_5	.0234452+	.0160176	.0167024	.0192328	.0159182	.0199289	.0183174	.0180199	.0017
P_6	.0000000	.0007536	.0007476	.0019044	.0049556	.0002106	.0023847	.0020406	.0018
$\langle\nu\rangle$	2.1540000*	2.1540000*	2.1540000*	2.1540000*	2.1540000*	2.1540000*	2.1540000*	2.1540000*	.005
$\langle\nu(\nu-1)\rangle$	3.7962	3.7328	3.7465	3.8162	3.7862	3.7797	3.8160	3.7889	.0290
$\langle\nu(\nu-1)(\nu-2)\rangle$	5.2528	5.0471	4.9803	5.2947	5.3196	5.1385	5.3193	5.2105	.1492
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.81820	.80454	.80749	.82250	.81604	.81465	.8224	.81663	.0063
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.3105	1.2471	1.2608	1.3304	1.3005	1.2940	1.3303	1.3032	.0290
$\langle\nu^2\rangle$	5.9502	5.8868	5.9005	5.9702	5.9402	5.9337	5.9700	5.9429	.0290

* data sets made to conform to this value

** data sets not used to form consensus because of several deviances beyond $\pm\sigma$

\+ means P_ν deviates by $> +\sigma$

\- means $P\nu$ deviates by $< -\sigma$

Table XXVI

P_ν for ^{241}Pu

	Gwin 84	Boldeman 84	Consensus	Std. Dev.
P_0	.0103533	.0110483	.0107008	.0005
P_1	.0880976	.0900637	.0890807	.0014
P_2	.2643341	.2667284	.2655313	.0017
P_3	.3343422	.3285560	.3314491	.0041
P_4	.2172018	.2117300	.2144659	.0039
P_5	.0716776	.0788167	.0752472	.0050
P_6	.0129416	.0095909	.0112663	.0024
P_7	.0010518	.0034661	.0006992	.0005
$\langle\nu\rangle$	2.9320000*	2.9320000*	2.9320000*	.008
$\langle\nu(\nu-1)\rangle$	7.0071	7.0552	7.0312	.0340
$\langle\nu(\nu-1)(\nu-2)\rangle$	13.2934	13.6606	13.4770	.2597
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.81510	.82069	.81790	.00395
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.3425	1.3906	1.3665	.0340
$\langle\nu^2\rangle$	9.9391	9.9872	9.9632	.0340

* data sets made to conform to this value

Table XXVII

P_ν for ^{242}Pu

	Hicks 56	Boldeman** 84	Std.Dev.
P_0	.0658845	.0679423	.0010
P_1	.1995462	.2293159	.0021
P_2	.3549338	.3341228	.0024
P_3	.3124876	.2475507	.0027
P_4	.0336161	.0996922	.0032
P_5	.0335318	.0182398	.0015
P_6	.0000000	.0031364	.0006
$\langle\nu\rangle$	2.1490000*	2.1490000*	.008
$\langle\nu(\nu-1)\rangle$	3.6588	3.8087	.036
$\langle\nu(\nu-1)(\nu-2)\rangle$	4.6936	5.3487	
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.79226	.82472	.002
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.1896	1.3395	.005
$\langle\nu^2\rangle$	5.8078	5.9577	.036

* data sets made to conform to this value

** because of the anomalous P_4 and P_5 in Hicks 56 it is recommended that Boldeman 84 be used alone; the Std.Dev. is as quoted in that paper, except for $\langle\nu\rangle$, where it is the evaluation of this paper

Table XXVIII

P_ν for ^{242}Cm

	Hicks 56	Halperin 80	Zhang 84	Consensus	Std. Dev.
P_0	.0166474-	.0228731	.0242445	.0212550	.0040
P_1	.1475553	.1340439	.1586229	.1467407	.0123
P_2	.3371507	.3291282	.3139804	.3267531	.0118
P_3	.3267925	.3389847+	.3147058-	.3268277	.0121
P_4	.1263383-	.1463070	.1398818	.1375090	.0102
P_5	.0414297	.0265274-	.0441874	.0373815	.010
P_6	.0033384+	.0020694	.0023659	.0025912	.0007
P_7	.0007477	.0000663	.0014512	.0007551	.0007
P_8	.000000	.000000	.0005602+	.0001867	.0003
$\langle\nu\rangle$	2.5400000*	2.5400000*	2.5400000*	2.5400000*	.02
$\langle\nu(\nu-1)\rangle$	5.1113	5.0433	5.2418	5.1321	.1009
$\langle\nu(\nu-1)(\nu-2)\rangle$	8.0363	7.3992	8.6735	8.0363	.6372
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.79225	.78171	.81248	.79548	.01564
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.1997	1.1317	1.3302	1.2205	.1009
$\langle\nu^2\rangle$	7.6513	7.5833	7.7818	7.6721	.1009

+ means P_ν deviates by $> + \sigma$

- means P_ν deviates by $< - \sigma$

* data sets made to conform to this value

Table XXIX

P_ν for ^{244}Cm

	Diven 56	Hicks 56	Dakovskii 74	Zhang 84	Consensus	Std. Dev.
P_0	.0128012	.0055032-	.0278773+	.0138381	.0150050	.0093
P_1	.1245815	.1186366	.0917423-	.1297295	.1161725	.0169
P_2	.3032554	.3013825	.3096042	.2851286-	.2998427	.0104
P_3	.3120112-	.3514536+	.3333684	.3358124	.3331614	.0162
P_4	.2011534+	.1763431	.1802425	.1773601	.1837748	.0117
P_5	.0289232-	.0412210	.0550183+	.0467494	.0429780	.0110
P_6	.0172741-	.0054600	.0021472-	.0102841	.0087914	.0066
P_7	.0000000	.0000000	.0000000	.0010977-	.0002744	.0005
$\langle\nu\rangle$	2.7200000*	2.7200000*	2.7200000*	2.7200000*	2.7200000*	.03
$\langle\nu(\nu-1)\rangle$	5.9891	5.8158	5.9471	6.0031	5.9388	.0853
$\langle\nu(\nu-1)(\nu-2)\rangle$	10.5080	9.4694	9.8848	10.5411	10.1008	.5180
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.80951	.78609	.80384	.81140	.80271	.01154
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.3107	1.1374	1.2687	1.3247	1.2604	.0853
$\langle\nu\rangle^2$	8.7091	8.5358	8.6671	8.7231	8.6588	.0853

+ means P_ν deviates by > + σ

- means P_ν deviates by < - σ

* data sets made to conform to this value

Table XXX

P_ν for ^{246}Cm

	Stoughton 73	Dakovskii 74	Consensus	Std. Dev.
P_0	.0130533	.0173831	.0152182	.0031
P_1	.0824850	.0700688	.0762769	.0088
P_2	.2512020	.2742057	.2627039	.0162
P_3	.3522395	.3376076	.3449236	.0103
P_4	.2258728	.2102577	.2180653	.0110
P_5	.0659829	.0851960	.0755895	.0139
P_6	.0091644	.0052810	.0072227	.0027
$\langle\nu\rangle$	2.9300000*	2.9300000*	2.9300000*	.03
$\langle\nu(\nu-1)\rangle$	6.9209	6.9595	6.9402	.0273
$\langle\nu(\nu-1)(\nu-2)\rangle$	12.5931	12.8173	12.7052	.1586
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.80617	.81067	.80842	.00318
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.2660	1.3046	1.2853	.0273
$\langle\nu^2\rangle$	9.8509	9.8900	9.8702	.0273

* data sets made to conform to this value

Table XXXI

P_ν for ^{248}Cm

	Boldeman 73	Stonghton 73	Consensus	Std. Dev.
P_0	.0063081	.0071623	.0067352	.0006
P_1	.0622386	.0570604	.0596495	.0037
P_2	.2272634	.2138438	.2205536	.0095
P_3	.3458147	.3559898	.3509030	.0072
P_4	.2435394	.2652139	.2543767	.0153
P_5	.0907591	.0879519	.0893555	.0020
P_6	.0206991	.0127780	.0167386	.0056
P_7	.0033775	.0000000	.0016888	.0024
$\langle\nu\rangle$	3.1300000*	3.1300000*	3.1300000*	.03
$\langle\nu(\nu-1)\rangle$	8.0299	7.8886	7.9592	.0999
$\langle\nu(\nu-1)(\nu-2)\rangle$	16.5585	15.3115	15.9350	.8818
$\langle\nu(\nu-1)\rangle/\langle\nu\rangle^2$	.81964	.80521	.81242	.0102
$\langle\nu^2\rangle-\langle\nu\rangle^2$	1.3630	1.2217	1.2923	.0999
$\langle\nu^2\rangle$	11.1599	11.0186	11.0892	.0999

• data sets made to conform to this value